Low Frequency Circulator/Isolator Uses No Ferrite or Magnet

By Charles Wenzel
Wenzel Associates, Inc.

This is the Grand Prize winner in the Design category of the 1991 RF Design Awards Contest. For his achievement, the author was awarded an HP 8591A portable spectrum analyzer from Hewlett Packard.

The ferrite circulator/isolator is an amazing and important tool for the microwave engineer. Unfortunately, for frequencies below several hundred megahertz, the size of the magnets and ferrite becomes unworkable and the cost skyrockets. With the advent of remarkably fast op-amps, it has become practical to construct a low power equivalent to the circulator that works all the way down to DC and exhibits superb reverse isolation and impedance characteristics to frequencies above 100 MHz.

Suitable for small signal applications, the active circulator is excellent for matching and tuning antennas, amplifiers, and oscillators. Figure 1 shows a schematic of the circuit. Figure 2 is a photo of the prototype of the device. The isolated 50 ohm resistance presented at each port makes experiments with non-linear or reactive devices such as detectors, mixers, frequency multipliers, and filters straightforward since both the signal source and the analyzer are isolated from the device under test. Engineers working with lower RF frequencies will find the active circulator to be a welcome addition to the test bench.

The purpose of the circulator is to absorb all energy entering a port and to pass that energy on to the next port. High reverse isolation ensures that the energy flows in one direction around the circulator and that the impedance of one port is not affected by the other ports. The microwave circulator uses the non-linear properties of ferrite immersed in a magnetic field whereas this circuit uses high speed operational amplifiers.

For the circulator to work properly, each port must exhibit the characteristics of a Thevenin equivalent consisting of a 50 ohm resistor and a voltage source with a voltage twice as large as the voltage arriving at the previous port. Note that this voltage source ignores signals leaving the previous port as well as any signals on any other ports. The factor of two makes up for the drop across the Thevenin resistance when a 50 ohm load is connected.

First, the 50 ohm resistance results from the two, 100 ohm resistors leading to virtual grounds — that is points that are held at a fixed voltage regardless of the current.

The Thevenin voltage source is a little less obvious since the two 100 ohm resistors are connected to two different voltages that average to the desired factor of two. Each op-amp amplifies its input signal by 3.236 which is applied to one of the resistors. A voltage divider drops this voltage down to 0.764 which is applied to the positive input of the next op-amp. Since the other resistor is connected to the feedback node of this op-amp, it sees the same 0.764 size signal. The average of 3.236 and 0.764 gives the desired factor of two. Figure 3 shows the forward gain versus frequency for different supply voltages. The differential gain is set so that signals leaving a port terminated with 50 ohms will generate no output at the following port. A load impedance other than 50 ohms generates a "reflection" which is passed on to the next port. The op-amps provide inherent reverse isolation as shown in Figure 5 and the power handling capability is shown in Figure 4.

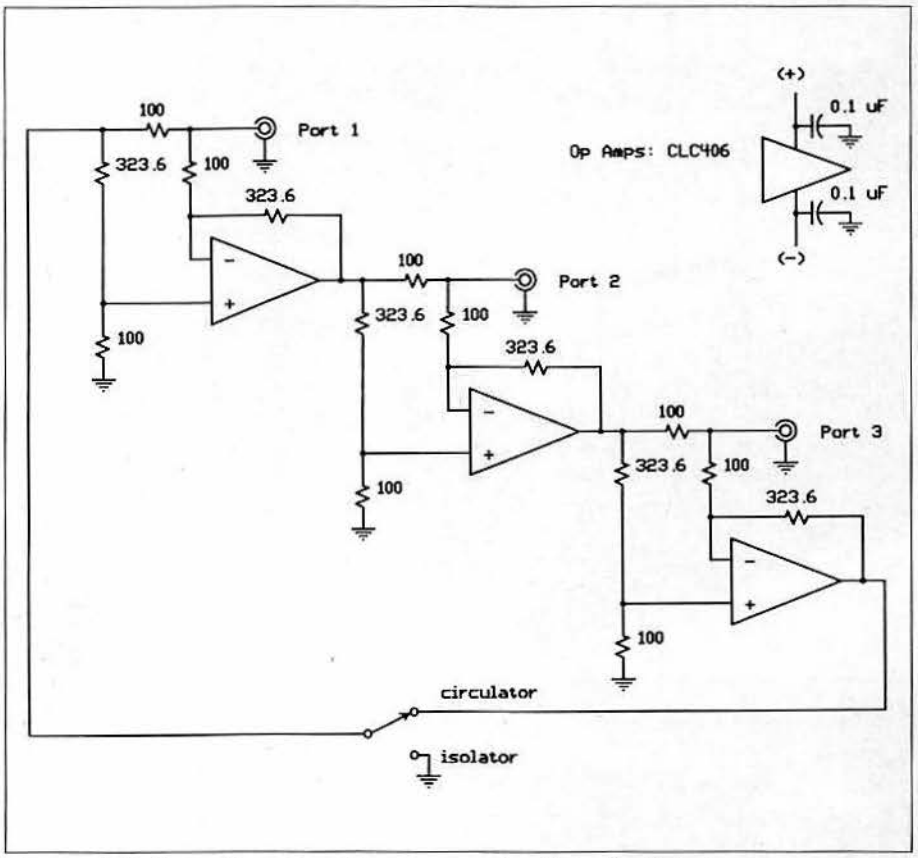


Figure 1. Schematic of low frequency circulator/isolator.

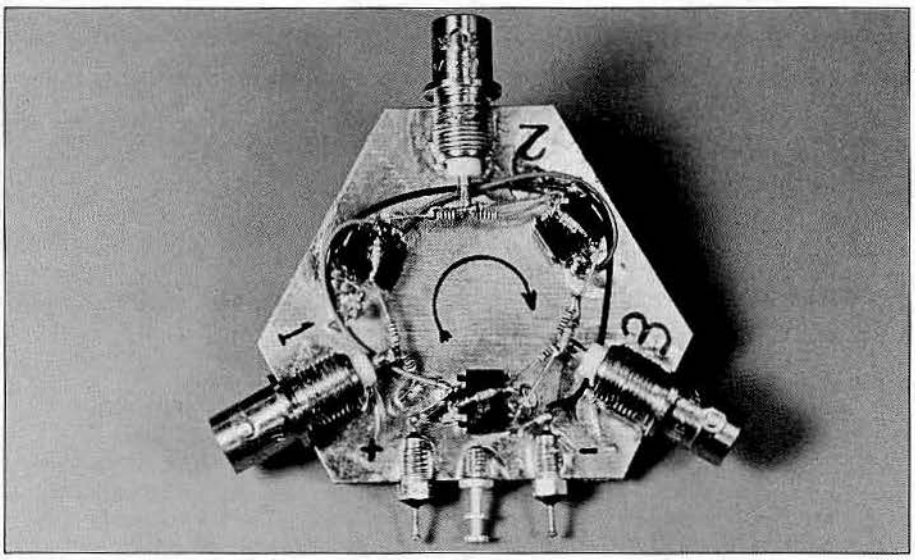


Figure 2. Constructed low frequency circulator/isolator.

The purist will note that a polarity reversal occurs from one port to the next due to the inverting op-amp configuration. More ports may be easily added to the circulator by repeating the obvious pattern.

Since the circulator works down to DC, its behavior can be observed with a multimeter. The port resistance can be measured with an ohm-meter and during the measurement the ohm-meter's test voltage appears at the next port (inverted). If -1 VDC is applied to port 1

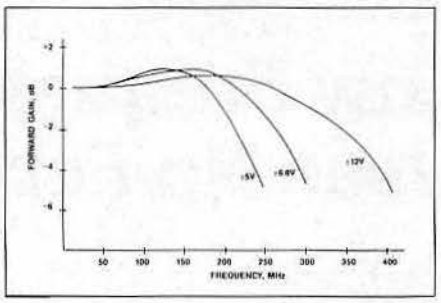


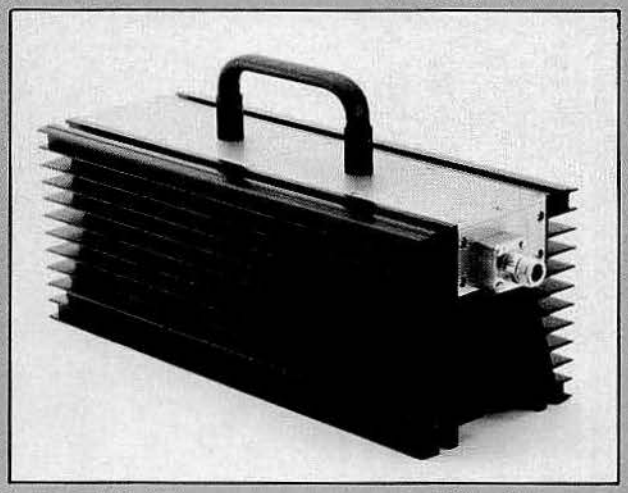
Figure 3. Forward gain versus frequency for different supply voltages.

then 1 VDC will appear across 50 ohms at port 2 and 0 VDC will appear at port 3 (as -1 VDC due to the op-amp inversion). Now if port 2 is shorted then the 1 VDC will "reflect in phase" and will destructively add to give 0 VDC at port 2 (an unusual way to describe why a short gives 0 VDC). This inverted volt circulates to port 3 where 1 VDC appears across the load!

Component Selection

The CLC406 op-amp selected for this

Fixed Attenuators



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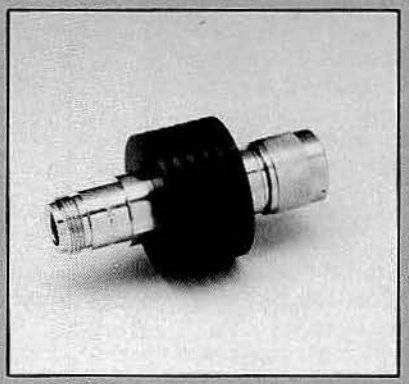
Frequency Range
DC-1000 MHz
Attenuation
3 thru 60 dB any 1 dB increment



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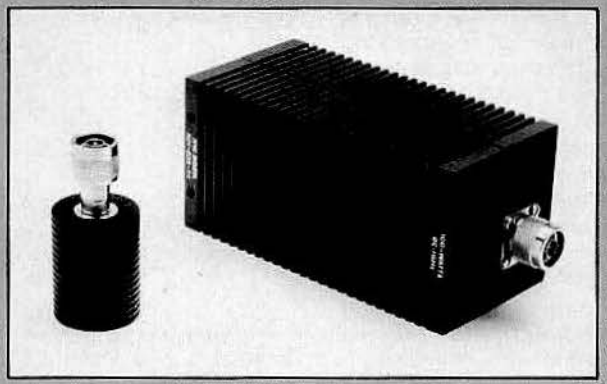

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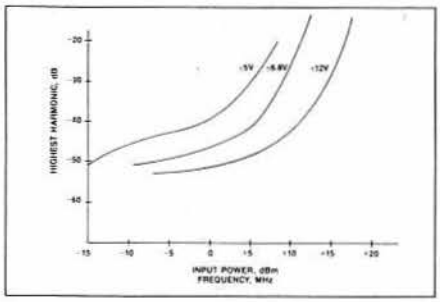

Figure 4. Distortion versus input power for different supply voltages.

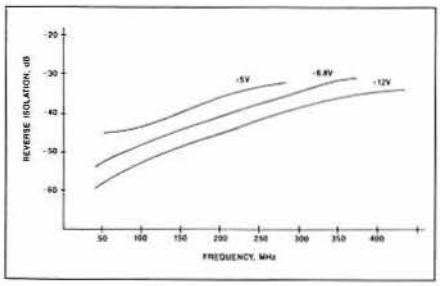

Figure 5. Reverse isolation versus frequency for different supply voltages.

design is not the fastest or highest power device that Comlinear Corporation manufactures, but instead represents the economy end of the spectrum with a price below $10. As Figures one through three show, this inexpensive amp delivers impressive performance at 5 VDC, even better performance near the absolute maximum rating at 6.8 VDC, and amazing performance well above its specified limit at 12 VDC! Operating above maximum ratings is not recommended. A better choice would be to select a faster, more powerful op-amp (or use sockets).

Stable, low inductance precision resistors are required for optimum results. The 323.6 ohm resistance can be achieved by paralleling a 330 ohm with a 16.8 kohm. The resistor values shown may be scaled to build a circulator with a different characteristic impedance. For example, a 75 ohm circulator would use resistors 1.5 times larger in all positions. It is interesting to note that a circulator could be built with a dif ferent characteristic impedance at each port.

Bypass capacitors must be connected to both power supply pins of each op-amp to the ground plane. The prototype uses 0.1 uF ceramic chip capacitors soldered directly from the IC to the ground plane.

Applications

The circulator is a natural choice for the matching and tuning of low level amplifiers. With the signal source connected to port 1, the amplifier's input or output to port 2, and a signal analyzer to port 3, the amplifier is turned for maximum return loss by adjusting for minimum signal at port 3. A high return loss is synonymous with a good VSWR since a well matched amplifier will "return," as a reflection, very little of the input signal. Figure 6 shows a typical application of the circulator/isolator.

Low level signal sources may also be adjusted for 50 ohm output impedance in a similar way. Simply adjust the frequency of the test signal until it is close to the carrier then tune the source for minimum reflection. Again, the re-

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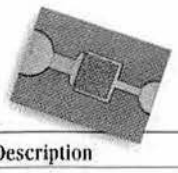

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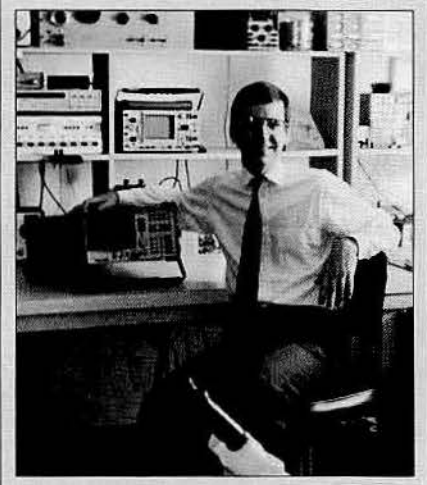
manner without using large signals that might cause interference with others. A low power generator is connected to port 1, the antenna to port 2, and some form of power or signal level indicator to port 3. The signal level at port 3 is proportional to the transmission loss and should be minimized by tuning the antenna matching network.

A time domain reflectometer is easily realized by applying a fast square wave or pulse to port 1 and connecting the device or cable under test to port 2. Breaks in the cable or other high impedance anomalies will reflect pulses with the same polarity as the input whereas shorts or lower impedances will reflect inverted pulses. Remember the inversion from one port to the next. A clean test signal is necessary for good results.

Conclusion

The active circulator brings many of the features of its big brother, the microwave ferrite circulator, down to the lower RF frequencies. Although the active version obviously lacks the power handling capabilities of typical circulators, the small signal applications abound. ***RF***



About the Author

Charles Wenzel is President of Wenzel Associates, a manufacturer of speciality crystal oscillator products for high purity, high stability applications. Founded in 1978, his company has developed high performance oscillators for instrumentation, communications, and military systems. Wenzel Associates has 36 employees, and boasts the world's lowest noise crystal oscillator, as measured by the National Institute of Standards and Technology (NIST).

His winning design was the result of considerable experimentation and design using discrete transistors, all of which failed to work. Recently-developed high-speed operational amplifiers allowed Charles to realize the goals of high isolation, stability, and controlled input and output impedances. He reports that a number of typical low-frequency op amp circuits were tried at RF using these devices, with good success.

Charles, a native of Austin, has a BSEE from the University of Texas. His hobbies include experimenting with new circuits and relaxing while playing his guitar. He can be reached at Wenzel Associates, Inc., 14050 Summit Drive, Austin, TX 78728; telephone (512) 244-7741.

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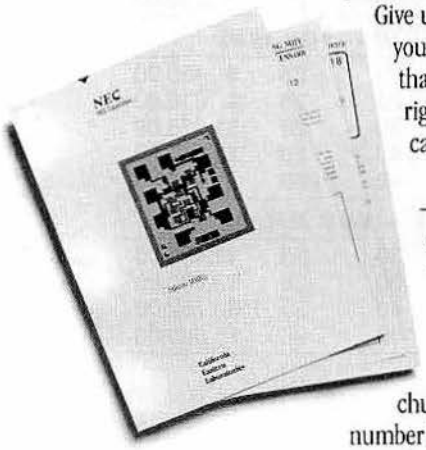

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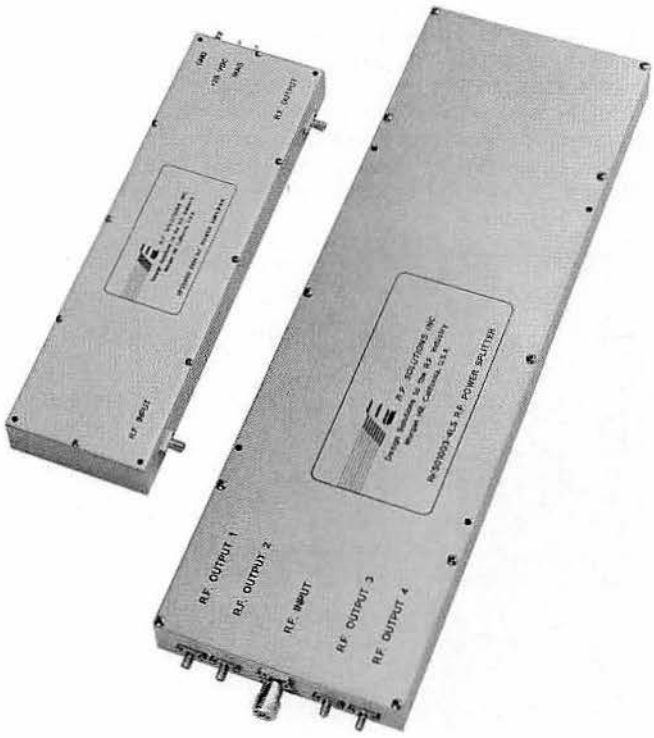
OFF THE SHELF

RF AMPLIFIERS

MODEL NUMBER	POWER Watts	GAIN dB	SUPPLY Volts	PRICE
FREQUENCY RANGE 5 – 50 MHz				
RFP0550-100	100	44	50	$2,100.00
RFP0550-1000	1000	16	50	$5,040.00
FREQUENCY RANGE 50 – 100 MHz				
RFP0800-100P50	50	30	50	$1,485.00
RFP0800-100P100	100	30	50	$1,660.00
RFP0800-100P200	200	30	50	$2,200.00
RFP800-100	600	16	50	$2,424.00
FREQUENCY RANGE 1 – 100 MHz				
RFP01100-300	300	46	50	$3,150.00
FREQUENCY RANGE 76 – 108 MHz				
RFP0810-600	600	16	50	$1,780.00
FREQUENCY RANGE 75 – 150 MHz				
RFP0800-150P50	50	30	50	$1,485.00
RFP0800-150P100	100	30	50	$1,660.00
RFP0800-150P200	200	30	50	$2,200.00
RFP800-150	500	14	50	$2,424.00
FREQUENCY RANGE 100 – 200 MHz				
RFP0800-200P50	50	30	50	$1,660.00
RFP0800-200P100	100	30	50	$2,900.00
RFP800-200	400	13	50	$3,636.00
FREQUENCY RANGE 225 – 400 MHz				
RFP0204-4	4	20	28	$ 484.00
RFP0204-10	10	30	28	$ 685.00
RFP0204-25	25	30	28	$1,140.00
RFP0204-50	50	40	28	$1,695.00
RFP0204-100	100	40	28	$2,200.00
FREQUENCY RANGE 400 – 500 MHz				
RFP0405-4	4	20	28	$ 435.00
RFP0405-10	10	30	28	$ 616.00
RFP0405-25	25	30	28	$1,026.00
RFP0405-50	50	40	28	$1,525.50
RFP0405-100	100	40	28	$1,980.00
FREQUENCY RANGE 1 – 500 MHz				
RFP00105-4	10	30	28	$1,450.00
RFP00105-25	25	30	28	$2,800.00
RFP00105-50	50	40	28	$3,752.00
RFP00105-100	100	40	28	$5,600.00



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MODEL NUMBER	INPUT/ OUTPUT PORTS	INSERTION LOSS dB	POWER Watts	PRICE
FREQUENCY RANGE 5 – 50 MHz				
RFS100-5-50-4	4	0.3	100	$ 360.00
RFS1000-5-50-4	4	0.3	1000	$ 610.00
FREQUENCY RANGE 50 – 1000 MHz				
RFS100-FL-FU-2	2	0.15	100	$ 500.00
RFS100-FL-FU-3	3	0.15	100	$ 600.00
RFS100-FL-FU-4	4	0.3	100	$ 800.00
RFS100-FL-FU-6	6	0.3	100	$1,000.00
RFS1000-FL-FU-2	2	0.15	1000	$ 750.00
RFS1000-FL-FU-3	3	0.15	1000	$ 900.00
RFS1000-FL-FU-4	4	0.3	1000	$1,200.00
RFS1000-FL-FU-6	6	0.3	1000	$1,500.00

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